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A REVIEW OF PROGRESSIVE COLLAPSE ANALYSIS IN TALL STEEL STRUCTURES

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ABSTRACT

Progressive collapse has become a major concern in the design and assessment of tall steel structures because local damage can propagate through the structural system and cause partial or total collapse that is disproportionate to the initiating event. This review examines the concept, causes, resistance mechanisms, analytical procedures, and current code provisions related to progressive collapse in tall steel buildings. The study highlights how factors such as column loss, transfer element failure, connection fracture, fire-induced degradation, and geometric irregularities can trigger collapse propagation. Particular emphasis is placed on the structural mechanisms that improve robustness, including alternate load path action, catenary action, Vierendeel action, diaphragm participation, continuity, and redundancy. The review also compares key design approaches, including tie-force method, alternate path method, and performance-based frameworks, while discussing the strengths and limitations of linear static, nonlinear static, linear dynamic, and nonlinear dynamic analyses. Special attention is given to modeling issues specific to tall steel structures, such as second-order effects, composite floor action, interaction between gravity and lateral systems, and realistic connection behavior. The study concludes that progressive collapse resistance in tall steel structures must be understood as a system-level property requiring integrated consideration of ductility, continuity, robustness, and realistic nonlinear response under abnormal loading scenarios.

Keywords: Progressive Collapse, Tall Steel Structures, Structural Robustness, Alternate Load Path, Catenary Action, Nonlinear Analysis

1 INTRODUCTION

Progressive collapse has evolved into a central concern in structural engineering due to the recognition that structural systems do not fail in isolation. A localized failure whether initiated by accidental loading, design deficiencies, construction errors, or extreme events can propagate through a structure in a highly nonlinear and often unpredictable manner. Unlike conventional limit-state failures, which are typically confined to individual components, progressive collapse is characterized by a chain reaction of failures that results in damage disproportionate to the initial cause. This phenomenon challenges traditional design philosophies that rely primarily on member-level strength and serviceability checks, necessitating a system level perspective focused on robustness, redundancy, and continuity. Historically, the significance of progressive collapse was underestimated, largely because structural design codes emphasized resistance to well defined loads such as gravity, wind, and seismic forces. However, catastrophic incidents fundamentally altered this perception. The partial collapse of the Ronan Point apartment building in 1968 demonstrated how the loss of a single load-bearing wall could trigger widespread structural failure. Decades later, the collapse of the World Trade Center towers during the September 11 attacks provided a more complex and large-scale illustration of how extreme events can initiate progressive collapse mechanisms in high-rise structures. Subsequent investigations conducted by the National Institute of Standards and Technology (NIST) emphasized the need for improved structural robustness, continuity of load paths, and better understanding of failure propagation under abnormal loading conditions. These findings directly influenced the development of modern design guidelines and regulatory frameworks. In response to these events, several authoritative documents were introduced to formalize progressive collapse mitigation strategies. Notably, the General Services Administration (GSA) guidelines and the Department of Defense Unified Facilities Criteria (UFC 4-023-03) established practical methodologies such as the Alternate Load Path (ALP) method, tie-force requirements, and enhanced local resistance approaches. These frameworks marked a transition from prescriptive rules toward more analytical and performance-based design philosophies. The focus shifted from merely preventing initial failure to ensuring that structures possess sufficient redundancy and ductility to arrest collapse progression after damage occurs.

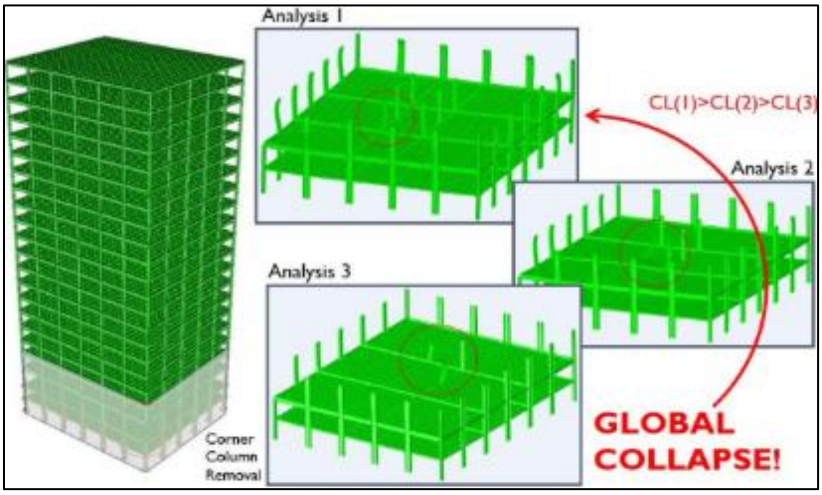

Figure 1: Sequential Column Removal Analysis Leading to Global Progressive Collapse in a Tall Steel Frame

Tall steel structures require particular attention within this domain due to their inherent structural characteristics. Unlike low- and mid-rise buildings, tall buildings exhibit increased geometric slenderness, higher axial load demands, and greater sensitivity to second-order effects such as P-Δ instability. The vertical and lateral load resisting systems in these structures are often highly integrated, involving moment-resisting frames, braced cores, outrigger systems, and belt trusses. While these systems enhance efficiency under normal loading conditions, they also introduce complexity in predicting load redistribution following localized damage. The failure of a critical component, such as a perimeter column or transfer girder, can disrupt both gravity and lateral load paths simultaneously, increasing the likelihood of progressive collapse. A defining feature of tall steel buildings is their reliance on beam-column connections and floor diaphragm systems to maintain structural integrity. Connections are not merely force-transfer mechanisms; they play a pivotal role in enabling ductility and redistribution capacity. Under progressive collapse scenarios, connections must sustain large rotations and deformations without brittle failure. The ability of beams to develop catenary action where axial tensile forces are mobilized after significant flexural deformation is another critical mechanism that contributes to collapse resistance. This behavior is highly dependent on connection detailing, material ductility, and continuity of framing systems. Inadequate connection performance can therefore negate the benefits of otherwise robust member design. Another important consideration is the presence of transfer levels and discontinuities within tall buildings. Architectural and functional requirements often necessitate irregular column layouts, leading to the use of transfer girders or trusses to redistribute loads. These elements become critical nodes within the structural system, and their failure can have disproportionate consequences. Similarly, outrigger and belt truss systems, commonly used to enhance lateral stiffness, introduce additional load paths that must be carefully evaluated under abnormal conditions. The interaction between these systems and the primary structural frame complicates the analysis of progressive collapse and requires detailed modeling approaches.

Traditional design methods based on linear elastic analysis are insufficient for capturing the complex behavior associated with progressive collapse. The phenomenon involves large deformations, material nonlinearity, dynamic effects, and potential fracture or connection failure. As a result, advanced analytical techniques such as nonlinear static (pushdown) analysis and nonlinear dynamic analysis have become essential tools in modern practice. These methods allow engineers to simulate the sudden removal of structural elements and evaluate the subsequent response of the system, including load redistribution, deformation patterns, and potential failure modes. However, the computational intensity and modeling challenges associated with these approaches remain significant barriers to widespread implementation. The conceptual shift from strength-based design to robustness-oriented design reflects a broader evolution in structural engineering philosophy. Robustness encompasses the ability of a structure to withstand unforeseen events without disproportionate damage, integrating concepts of redundancy, ductility, and alternative load paths. In tall steel structures, achieving robustness requires careful consideration of system level behavior rather than isolated component performance. This includes ensuring continuity of load paths across floors, enhancing connection ductility, and providing sufficient redundancy to accommodate localized damage without triggering collapse. Despite substantial progress, several challenges persist in the field of progressive collapse analysis. There is no universally accepted framework that balances accuracy and practicality, particularly for tall steel structures with complex geometries and load-resisting systems. Experimental data at full scale remain limited, especially for high-rise configurations, constraining the validation of analytical models. Additionally, uncertainties associated with material behavior, connection performance, and extreme loading scenarios introduce further complexity into the design process. This review addresses these challenges by synthesizing current knowledge on progressive collapse analysis in tall steel structures. The discussion encompasses fundamental mechanisms of collapse propagation, analytical methodologies, design guidelines, and the role of structural components such as connections and diaphragms. Emphasis is placed on understanding how system-level behavior governs collapse resistance and how modern design approaches can enhance structural robustness. The review also identifies gaps in existing research and outlines potential directions for future investigation, with the objective of advancing both theoretical understanding and practical application in this critical area of structural engineering.

2 CONCEPT AND DEFINITION OF PROGRESSIVE COLLAPSE

Progressive collapse is formally defined as a structural failure mechanism in which localized damage triggers a chain reaction of subsequent failures, resulting in partial or total collapse that is disproportionate to the initiating event. This definition emphasizes two essential attributes: the initiating damage is limited in extent, and the resulting structural consequences exceed what would be expected based solely on that initial disturbance. The concept is therefore inherently system-oriented, requiring evaluation of how forces redistribute and how structural components interact under abnormal conditions. Modern design frameworks interpret progressive collapse not simply as a failure condition, but as a performance problem associated with structural robustness. The Department of Defense Unified Facilities Criteria (UFC 4-023-03) defines the objective as reducing the potential for collapse following localized damage caused by events that are not explicitly considered in standard design load combinations. Similarly, the General Services Administration guidelines emphasize the ability of a structure to sustain damage without experiencing disproportionate consequences, primarily through the provision of alternate load paths. More recently, American Society of Civil Engineers Standard ASCE/SEI 76-23 extends this perspective by adopting a performance-based framework, where acceptable levels of damage and collapse resistance are defined in probabilistic and risk-informed terms rather than purely prescriptive rules. Within tall steel structures, progressive collapse cannot be characterized as a single, isolated failure mode. Instead, it is a sequence-driven phenomenon governed by a combination of material behavior, connection performance, geometric nonlinearity, and dynamic effects. The process typically begins with damage initiation, such as the sudden removal of a column due to impact, blast, or design deficiency. This initial disturbance disrupts the established load path, forcing adjacent structural elements to absorb and redistribute the imposed loads. The structural response at this stage is dominated by transient dynamic effects, including inertia forces and rapid stress redistribution. Following the initial redistribution, the structure enters a phase of localized response, where individual components may experience yielding, buckling, or fracture. In steel systems, beams may transition from flexural behavior to axial tension-dominated behavior, activating catenary action if sufficient rotational capacity and connection integrity are present. Connections play a decisive role during this phase; their ability to sustain large deformations without brittle failure determines whether load redistribution can continue or whether additional elements will fail. If connections fracture prematurely, the redistribution process is interrupted, increasing the likelihood of progressive collapse. As the sequence evolves, member instability and geometric nonlinearity become increasingly significant. Second-order effects, particularly P-Δ behavior, amplify displacements and internal forces, potentially accelerating failure propagation. Floor systems and diaphragms also contribute to the structural response by facilitating load sharing across adjacent bays and framing lines. In tall buildings, where structural systems are highly interconnected, the failure of a single element may influence both vertical and lateral load-resisting mechanisms, further complicating the collapse process.

The distinction between localized damage and disproportionate collapse is fundamentally linked to the concept of alternate load paths. A structure capable of redistributing loads through multiple independent paths can isolate damage and prevent its spread. Conversely, systems with limited redundancy or poor continuity are more susceptible to cascading failures. This distinction reframes the design objective: the critical issue is not whether an individual element fails, but whether the structural system as a whole can accommodate that failure without losing overall stability. Three key attributes govern this capability. First, reserve strength ensures that adjacent members possess sufficient capacity to carry additional loads after redistribution. Second, deformation capacity, or ductility, allows structural components and connections to undergo large inelastic deformations without sudden loss of resistance. Third, continuity ensures that load paths remain intact across the structure, enabling effective force transfer between components. Deficiencies in any of these attributes can compromise the structure's ability to resist progressive collapse. In practical terms, progressive collapse assessment requires explicit consideration of abnormal loading scenarios, most commonly simulated through the notional removal of critical structural elements. Analytical methods must capture nonlinear material behavior, large deformations, and dynamic effects to accurately represent the sequence of events following damage. This requirement distinguishes progressive collapse analysis from conventional design approaches, which typically rely on linear elastic assumptions and predefined load combinations. The evolution of design philosophy from prescriptive tie-force rules to performance-based robustness frameworks reflects an increasing recognition of the complexity inherent in progressive collapse phenomena. For tall steel structures, this evolution is particularly significant due to their scale, structural complexity, and reliance on connection behavior. A comprehensive understanding of progressive collapse therefore requires integration of system-level analysis, detailed component modeling, and an appreciation of the interaction between structural subsystems under extreme conditions.

Table 1: Summary of Selected Studies on Progressive Collapse Analysis of Steel and Building Structures

Study	**Structural system**	**Method / approach**	**Main focus**	**Key findings**
Rahnavard et al. (2018)	Tall steel-composite high-rise buildings with regular and irregular plans; moment frame and moment + braced frame systems	3D finite element nonlinear dynamic analysis in ABAQUS under column removal scenarios	Effect of plan irregularity, lateral resistance system, and removed column location	Side-column removal was more critical than corner removal. Irregular models showed poorer performance, and the study recommended checking columns for DL + 0.25LL to reduce collapse risk.
Ghogare & Daule (2021)	Steel structures under progressive collapse	Literature review of direct/indirect design methods, UFC/GSA-based understanding, and prior steel studies	Overview of collapse mechanisms, events, and analysis approaches for steel buildings	Highlights that progressive collapse in steel frames is linked to redistribution after loss of key members; emphasizes need for analysis because full-scale tests are costly and limited.
Wang et al. (2014)	Building structures broadly, including steel and concrete systems	Review organized around experimental study, numerical simulation, theoretical analysis, and design methods	State-of-the-art development in progressive collapse research	Shows that most experiments rely on static loading, while dynamic effects remain underexplored; also notes that practical, engineering-friendly robustness assessment methods are still lacking.
Lotfy et al. (2022)	25-story composite steel tall building with five spans in each direction	3D nonlinear dynamic time-history analysis with probabilistic assessment	Influence of concrete grade, steel grade, slab reinforcement, beam section, bracing position, and removed-column location	Concrete grade, removed-column position, beam section, and bracing location significantly affected response; steel grade and bottom reinforcement density were less influential. Corner/exterior removal produced the most critical axial force and plastic strain responses.
Ferraioli et al. (2022)	Existing multistory steel braced office building in Naples, Italy	Nonlinear static and dynamic alternate path analyses under different column-loss scenarios; retrofit verification	Robustness of an older real building and effectiveness of retrofit	Simple braced frames were vulnerable because of weak brace connections. Joint strengthening was impractical, but an outrigger-belt truss / Vierendeel-based retrofit improved collapse resistance and reduced vertical displacement by about 21–30%.

Yuzbasi & Isik (2026)	Six-story steel moment-resisting frame	Applied Element Method (AEM) under various column-removal scenarios, with robustness emphasis	Progressive collapse behavior and robustness of multi-story steel frames, especially in seismic context	Frames were examined as systems where local member loss can propagate into disproportionate failure; the paper stresses the importance of connection behavior, redistribution capacity, and combined seismic-progressive collapse thinking.
Tavakoli, Rashidi Alashti & Abdollahzadeh (2012)	Seismically designed multi-story steel braced dual systems with moment frames and concentric bracing	2D and 3D nonlinear static push-over analysis using alternate load path method	Progressive collapse under seismic loading after loss of critical members	Number of bays, building height, and eliminated-element location strongly influenced collapse potential. Buildings with more stories and bays showed better robustness, and the study adapted UFC/GSA concepts for seismic progressive collapse evaluation.

3 CAUSES OF PROGRESSIVE COLLAPSE IN TALL STEEL STRUCTURES

Progressive collapse in tall steel structures is initiated by a wide spectrum of triggering events that can be broadly categorized as accidental, malicious, natural, or design-related. Contemporary design standards emphasize that collapse mitigation strategies must remain independent of the specific initiating cause. This principle reflects the inherent uncertainty associated with extreme events and the necessity of ensuring structural robustness under unforeseen conditions. Rather than designing for isolated scenarios, modern approaches focus on enabling the structure to tolerate localized damage without disproportionate consequences. Authoritative frameworks such as those developed by the American Society of Civil Engineers recognize that initial failure may result from diverse sources, including vehicle impact, blast loading, severe environmental actions, or deficiencies in design and construction. These initiating events share a common characteristic: they compromise a critical structural component, thereby disrupting the established load path and forcing the structure to undergo rapid redistribution of forces. The severity of the resulting response depends not only on the nature of the initiating event but also on the structural configuration and capacity for alternative load transfer. In tall steel structures, certain triggers are particularly critical due to the scale, complexity, and load distribution characteristics of these systems. One of the most significant scenarios is the sudden loss of a primary vertical load-bearing element, such as a perimeter, corner, or interior column. Columns in high-rise buildings carry substantial accumulated gravity loads from multiple floors, and their removal induces immediate and substantial load redistribution to adjacent members. The resulting demand may exceed the capacity of surrounding beams and connections, especially if these elements are not designed for such abnormal conditions.

Failure of transfer elements represents another major cause of progressive collapse. Transfer girders or trusses are commonly used in tall buildings to accommodate architectural or functional requirements, such as open podium levels or changes in column layout. These elements act as critical nodes within the load path hierarchy, supporting significant portions of the structure above. Their failure can therefore lead to a sudden and extensive redistribution of loads, often with limited redundancy available to compensate for the loss. This condition significantly increases the risk of disproportionate collapse. Connection failure is equally critical in steel structures, where joints govern both strength and ductility. Under abnormal loading conditions, beam-column connections are subjected to combined moment, shear, and axial forces that may exceed their design limits. If connections lack sufficient ductility or are prone to brittle fracture, they may fail prematurely, interrupting load redistribution and accelerating collapse propagation. The integrity of connections is therefore a determining factor in the structural system's ability to sustain localized damage. Fire-induced degradation introduces a distinct and complex failure mechanism. Elevated temperatures reduce the strength and stiffness of steel, leading to progressive weakening of structural members. Columns are particularly vulnerable, as their loss of axial capacity can trigger instability and load redistribution. At the same time, beams may develop catenary action, and floor systems may exhibit tensile membrane action, both of which can contribute to collapse resistance. However, the effectiveness of these mechanisms depends on boundary conditions, temperature gradients, load levels, and the interaction between heated and unheated components. Uneven thermal expansion and restraint can also induce additional forces that exacerbate structural distress.

The severity of these causes is amplified in tall steel structures due to their inherent characteristics. The accumulation of gravity loads with height results in higher demand on lower structural elements, while the complexity of load paths increases the difficulty of achieving effective redistribution. Additionally, the interaction between gravity and lateral load-resisting systems means that local damage can have system-wide implications, affecting both vertical stability and lateral resistance. Overall, the causes of progressive collapse in tall steel structures are multifaceted and interdependent.

Effective mitigation requires not only identification of potential triggers but also a comprehensive understanding of how these triggers interact with structural configuration, material behavior, and system-level response.

4 PROGRESSIVE COLLAPSE RESISTANCE MECHANISMS

Progressive collapse resistance in tall steel structures is governed by a set of interrelated mechanisms that enable the structure to sustain localized damage without triggering disproportionate failure. These mechanisms operate beyond the elastic range of behavior and rely heavily on ductility, continuity, and system-level interaction. Unlike conventional design, which focuses on member strength under predefined loads, progressive collapse design emphasizes the ability of the structure to redistribute forces and maintain stability after the loss of critical elements. The alternate load path (ALP) method forms the foundation of modern progressive collapse design. This approach assumes that the removal of a key vertical load-bearing member, such as a column, should not result in immediate collapse if the structure possesses sufficient redundancy. Instead, loads must be redistributed through adjacent beams, columns, and floor systems. Design guidelines from the General Services Administration and the Department of Defense adopt this methodology by requiring engineers to simulate column removal scenarios and evaluate whether the remaining structure can sustain the redistributed loads. In tall steel buildings, the effectiveness of alternate load paths depends on the continuity of framing systems, the stiffness of floor diaphragms, and the integrity of beam-column connections. Structures with discontinuities or weak connections exhibit limited redistribution capacity and are more susceptible to collapse propagation. Catenary action represents one of the most critical resistance mechanisms in steel frames following severe vertical support loss. When beams experience large deflections after column removal, their flexural capacity becomes insufficient to resist applied loads. At this stage, axial tensile forces develop within the beam, allowing it to act as a tension tie between supports. This transformation significantly enhances load-carrying capacity and can prevent collapse if properly mobilized. However, the development of catenary action is highly dependent on connection behavior. Beam-column joints must sustain large rotations and axial forces without brittle fracture. If connections fail prematurely, the catenary mechanism cannot develop, leading to rapid loss of load-carrying capacity. Therefore, connection ductility and rotational capacity are critical design considerations in tall steel structures.

Table 2: Summary of Progressive Collapse Resistance Mechanisms and Their Structural Roles in Tall Steel Structures

Mechanism	Description	Structural Behavior	Key Requirements	Limitations
Alternate Load Path (ALP)	Redistribution of loads after removal of a critical element	Load transfer through adjacent beams, columns, and floor systems	Structural redundancy, continuous framing, strong connections	Insufficient redundancy leads to overload and cascading failure
Catenary Action	Beams develop axial tension after large deflection	Transition from flexural to tension-dominated behavior	High connection ductility, rotation capacity, tensile resistance	Connection fracture prevents development of catenary forces
Vierendeel Action	Load redistribution through bending and shear in frame bays	Double curvature deformation in beams and columns	Rigid/semi-rigid connections, member continuity	Limited efficiency; high bending demand may cause local failure
Redundancy	Availability of multiple load paths within the structure	Load sharing across different structural components	Multi-bay framing, integrated systems	Lack of redundancy increases collapse propagation risk
Continuity	Uninterrupted load transfer through structural elements	Enables force redistribution and deformation compatibility	Continuous ties, robust connections	Discontinuities disrupt load paths and reduce robustness
Composite Action	Interaction between steel beams and concrete slabs	Increased stiffness and improved load distribution	Shear connectors, slab integrity, diaphragm action	Loss of composite action reduces stiffness and redistribution capacity
Diaphragm Action	Floor systems distribute loads laterally across the structure	Load sharing between multiple frames or bays	Adequate in-plane stiffness and connectivity	Weak diaphragms lead to localized overloads

Vierendeel action provides an additional mechanism for load redistribution, particularly in rigid frame systems. This behavior occurs when structural bays deform in double curvature, causing beams and columns to resist loads through combined bending and shear rather than axial forces. In progressive collapse scenarios, Vierendeel action becomes significant when adjacent members remain continuous and capable of sustaining inelastic deformation. Following the loss of a column, the surrounding frame can redistribute loads through moment transfer across multiple bays. Although this mechanism is generally less efficient than catenary action in terms of ultimate strength, it contributes to the overall robustness of the structure by providing an alternative load path. Its effectiveness depends on the stiffness and continuity of connections, as well as the ability of members to sustain large bending deformations. System-level characteristics such as redundancy, continuity, and composite action are essential for enabling these mechanisms. Redundancy ensures that multiple load paths are available, allowing the structure to tolerate the loss of individual components. In tall steel buildings, redundancy is achieved through multi-bay framing systems and integration of vertical and lateral load-resisting elements. Continuity of structural members and connections facilitates effective force transfer, which is necessary for both catenary and Vierendeel actions to develop. Discontinuities, such as transfer levels or irregular geometries, can interrupt load paths and reduce collapse resistance.

Composite action between steel beams and concrete floor slabs further enhances structural performance. The slab increases stiffness, improves load distribution, and contributes to energy absorption during large deformations. Floor diaphragms also play a critical role in redistributing loads across the structure, reducing the demand on individual members. Overall, progressive collapse resistance in tall steel structures depends on the combined performance of these mechanisms, requiring a comprehensive system-level design approach that integrates strength, ductility, and continuity.

5 DESIGN APPROACHES AND CODE PROVISIONS

Design approaches for progressive collapse mitigation in tall steel structures have transitioned from simplified prescriptive rules to more advanced analytical and performance-based frameworks. These approaches differ in their ability to capture actual structural behavior under abnormal loading conditions and are applied based on the complexity and importance of the structure. The tie-force method represents an indirect and simplified approach that requires the provision of adequate horizontal and vertical ties throughout the structure. These ties are intended to maintain structural integrity after localized damage by preventing separation of structural components. While this method is straightforward and suitable for preliminary design, it does not explicitly account for nonlinear behavior, dynamic effects, or load redistribution mechanisms. In tall steel structures, where irregularities and complex load paths are common, reliance solely on tie-force provisions is insufficient to ensure robustness. The alternate path method is a direct analysis approach and is widely regarded as the primary tool for progressive collapse assessment. In this method, a critical load-bearing element, typically a column, is notionally removed, and the response of the remaining structure is evaluated. This approach directly examines the ability of the structure to redistribute loads and maintain stability. Design guidelines from the Department of Defense and the General Services Administration adopt this methodology, providing specific requirements for loading conditions and acceptance criteria. The method is particularly effective for tall steel structures because it captures system-level behavior, including the influence of connections and large deformations.

Key element design is another approach in which selected critical members are designed to resist specified abnormal loads without failure. This method reduces the likelihood of initiating events by strengthening essential components. However, in tall steel structures, this approach does not address the overall system response and may shift vulnerability to other elements if used in isolation. Recent developments emphasize performance-based design frameworks, particularly through the American Society of Civil Engineers Standard ASCE/SEI 76-23. This approach defines performance objectives based on risk and structural importance, allowing for more flexible and realistic assessment of collapse resistance. It integrates advanced analysis methods and focuses on system robustness rather than individual component strength. This shift reflects the need for more comprehensive design strategies in complex tall steel structures.

6 ANALYTICAL PROCEDURES FOR PROGRESSIVE COLLAPSE

Progressive collapse analysis requires specialized analytical procedures capable of capturing the complex sequence of events that follows localized structural damage. These procedures are generally classified into four categories: linear static, nonlinear static, linear dynamic, and nonlinear dynamic analysis. The selection of an appropriate method depends on the level of accuracy required, the structural complexity, and the expected degree of nonlinearity in the response. For tall steel structures, where large deformations and connection behavior play a dominant role, simplified methods often provide limited reliability. Linear static analysis represents the most basic approach and is primarily used as a preliminary screening tool. In this method, the effects of sudden member removal are approximated by applying amplified static loads to the remaining structure. These amplification factors are intended to simulate dynamic effects such as inertia. The method is computationally efficient and easy to implement, making it attractive for initial assessments. However, it is inherently limited because it assumes linear elastic behavior and cannot capture key phenomena such as yielding, large deformations, or instability. In tall steel structures, where progressive collapse response is strongly nonlinear, linear static analysis may significantly underestimate or misrepresent structural behavior. Nonlinear static analysis, commonly referred to as pushdown analysis, provides a more realistic representation of structural response by incorporating material and geometric nonlinearity. In this approach, loads are incrementally applied to the damaged structure, and the resulting load–displacement relationship is evaluated. This method allows for the identification of plastic hinge formation, redistribution of internal forces, and overall deformation capacity. It is widely used in engineering practice because it offers a balance between accuracy and computational efficiency. For tall steel structures, nonlinear static analysis is particularly useful for assessing reserve strength and identifying critical failure mechanisms. However, it does not account for dynamic effects associated with sudden element removal, such as inertia and transient force redistribution, which can be significant in progressive collapse scenarios.

Linear dynamic analysis introduces time-dependent effects and includes inertia forces, making it more representative of sudden damage events than static approaches. In this method, the structural response is evaluated using dynamic equations of motion while maintaining linear elastic material behavior. Although it captures the immediate dynamic response following member removal, it still neglects inelastic behavior, which is essential for understanding collapse progression. As a result, its applicability to tall steel structures is limited, particularly when the response involves extensive yielding, connection deformation, or large displacements. Nonlinear dynamic analysis is the most comprehensive and rigorous method for progressive collapse assessment. It combines time-dependent analysis with nonlinear material and geometric behavior, allowing for accurate simulation of the entire collapse sequence. This approach captures critical aspects such as inertia effects, plastic deformation, catenary action, connection response, and P-Δ instability. It also enables the evaluation of failure propagation and interaction between structural components. Research on steel frames consistently demonstrates that nonlinear dynamic analysis provides the most realistic prediction of progressive collapse behavior. Despite its advantages, nonlinear dynamic analysis is computationally demanding and requires detailed modeling of structural components, including connections and material properties. The accuracy of the results is highly sensitive to modeling assumptions, such as boundary conditions, damping, and failure criteria. For tall steel structures with complex configurations, including transfer levels and irregular geometries, careful model development and validation are essential.

In practice, progressive collapse assessment often involves a hierarchical approach, where simpler methods are used for initial screening, followed by more advanced analyses for critical scenarios. However, for tall steel structures, reliance on simplified methods alone is inadequate. Accurate evaluation of collapse resistance requires analytical procedures capable of capturing nonlinear and dynamic behavior, making nonlinear dynamic analysis the preferred approach for detailed assessment.

7 MODELING ISSUES SPECIFIC TO TALL STEEL STRUCTURES

Accurate modeling of progressive collapse in tall steel structures presents significant challenges due to the complexity of their geometry, load paths, and component interactions. A fundamental limitation in existing research is the widespread use of simplified low- and mid-rise frames as surrogate models. While these studies provide useful insights, they fail to capture the distinctive behaviors of tall buildings, resulting in a gap between analytical predictions and actual structural performance. Tall steel structures exhibit pronounced second-order (P-Δ) effects due to their height, slenderness, and high axial loads. These effects amplify displacements and internal forces following localized damage, accelerating instability and collapse propagation. Simplified models that neglect geometric nonlinearity cannot accurately represent this behavior, leading to unconservative results. Additionally, tall buildings experience substantial axial-force redistribution when a vertical load-bearing element is removed. The redistribution demand increases with building height, placing greater stress on adjacent columns and connections, particularly at lower levels where gravity loads accumulate. Connection modeling represents one of the most critical and challenging aspects of progressive collapse analysis. Studies associated with the University of Southampton highlight that steel connections are often the most vulnerable components under abnormal loading. In many analytical models, connections are idealized as either perfectly rigid or pinned, which does not reflect their actual nonlinear behavior. In reality, connections exhibit complex responses involving stiffness degradation, plastic rotation, and potential fracture under combined axial tension, shear, and moment reversal. In tall steel structures, these demands are significantly amplified due to large deformations and dynamic effects. Inaccurate representation of connection behavior can therefore lead to substantial errors in predicting load redistribution and collapse resistance. Another critical modeling issue is the interaction between gravity framing and lateral load-resisting systems. Tall buildings typically incorporate integrated systems such as moment frames, braced cores, and outrigger or belt truss configurations. These systems are designed to work together under normal loading conditions, but their interaction becomes more complex after localized damage. The removal of a structural element may simultaneously affect both vertical load transfer and lateral stability, creating coupled responses that are difficult to capture without detailed system-level modeling.

Geometric irregularities further complicate analysis. Features such as transfer stories, setbacks, podium levels, and outrigger systems introduce discontinuities in load paths and stiffness distribution. These irregularities can lead to localized concentrations of stress and deformation, increasing the likelihood of failure under abnormal conditions. Standardized modeling approaches often fail to adequately represent these features, resulting in oversimplified predictions of structural behavior. Composite floor action is another factor that is frequently underrepresented in analytical studies. In practice, tall steel buildings rely heavily on steel–concrete composite floor systems, which provide significant योगदान to stiffness, load distribution, and energy dissipation. Floor diaphragms facilitate load sharing across multiple frames, enhancing redundancy and robustness. However, many simplified models neglect slab participation or assume idealized behavior. This omission can lead to inaccurate assessments: neglecting composite action may underestimate structural capacity, while ignoring potential slab cracking, shear connector failure, or membrane action limits may lead to overestimation of robustness. Model fidelity is therefore central to credible progressive collapse assessment. High-fidelity models must incorporate nonlinear material behavior, realistic connection characteristics, geometric nonlinearity, and system-level interactions. While such models are computationally demanding, they are necessary for capturing the true response of tall steel structures under abnormal loading conditions. Without adequate modeling detail, the reliability of progressive collapse predictions remains uncertain, particularly for complex high-rise systems.

8 EXPERIMENTAL AND NUMERICAL RESEARCH TRENDS

Experimental research on progressive collapse in steel structures remains limited due to the high cost and technical difficulty of conducting full-scale sudden column removal tests. Most available studies rely on quasi-static or pseudo-dynamic testing of large-scale frames. These experiments demonstrate that collapse resistance is strongly influenced by loading patterns, connection performance, and structural continuity. The results consistently indicate that post-damage behavior cannot be accurately predicted using elastic analysis alone, as it depends on complex interactions between bending, axial tension, and connection rotation capacity. Connection behavior has emerged as a critical factor in experimental observations. Beam-column joints must sustain large deformations and combined force effects to enable mechanisms such as catenary action. If connections exhibit brittle failure, the redistribution process is interrupted, significantly increasing the likelihood of collapse. These findings highlight the importance of ductile detailing and realistic modeling of joint behavior in progressive collapse assessment.

Due to the limitations of experimental studies, numerical simulation dominates current research. Advanced finite element models are widely used to analyze progressive collapse in moment-resisting frames, braced systems, and composite structures. These models allow detailed investigation of load redistribution, dynamic response, and failure propagation under various column removal scenarios. Numerical studies consistently show that redundancy, continuity, and ductile connections enhance collapse resistance, while brittle fracture and local instability govern failure. Recent research trends focus on developing simplified analytical methods that bridge the gap between complex simulations and practical design. These approaches aim to capture essential nonlinear behavior while remaining computationally efficient, making them suitable for engineering applications.

9 RESEARCH GAPS

Despite significant advancements in progressive collapse research, several critical gaps remain, particularly for tall steel structures. One major limitation is the reliance on idealized column-removal scenarios, which, although useful for standardization, do not fully represent the range of realistic hazards encountered in practice. Actual initiating events often involve complex loading conditions and damage patterns that are not captured by simplified assumptions. Another important gap is the limited understanding of structural performance under combined or sequential hazards, such as blast followed by fire, impact-induced damage with subsequent thermal effects, or seismic damage preceding collapse. These multi-hazard scenarios introduce coupled mechanisms that significantly influence collapse progression but remain insufficiently explored.

The interaction between global stability systems and local gravity load redistribution also requires further investigation. In tall buildings, lateral systems such as outriggers and cores interact with gravity framing, yet many simplified analytical procedures do not adequately capture this coupling, leading to incomplete assessment of structural response. Uncertainty in connection fracture modeling represents another critical issue. Accurate prediction of connection behavior under high strain rates or elevated temperatures remains challenging, limiting the reliability of analytical models. Finally, while design standards are moving toward performance-based approaches, practical and universally accepted robustness metrics for tall steel structures are still under development, hindering consistent implementation in engineering practice.

10 CONCLUSION

Progressive collapse analysis in tall steel structures has evolved from prescriptive integrity rules to more explicit direct-analysis and performance-based robustness frameworks. Contemporary standards and guidelines, including UFC 4-023-03, GSA guidance, and ASCE/SEI 76-23, recognize the need to assess structural response after local damage and to ensure that collapse does not propagate disproportionately. For tall steel buildings, the problem is particularly complex because resistance depends not only on member strength but also on continuity, redundancy, connection ductility, catenary action, Vierendeel action, diaphragm participation, and global stability effects. The review indicates that nonlinear dynamic analysis remains the most reliable tool for critical assessments, while nonlinear static analysis serves as a practical intermediate method. Simplified linear procedures are useful for screening but are often insufficient for tall, irregular, or connection-sensitive steel systems. Future research should move beyond generic frame models and focus on tall-building-specific configurations, realistic multi-hazard damage scenarios, validated connection fracture models, and resilience-oriented performance criteria. In summary, the progressive collapse resistance of tall steel structures should be treated as a system property, not a member-level check, and successful mitigation requires design that integrates robustness, ductility, continuity, and realistic nonlinear response.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Disclosure of conflict of interest

The authors declare no conflicts of interest regarding this manuscript.

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